Pergamon

0196-8904(94)00030-1

Energy Convers. Mgmt Vol. 36, No. 1, pp. 65–77, 1995

0196-8904/95 $9.50 + 0.00

BIOMASS-FIRED STEAM POWER COGENERATION SYSTEM: A THEORETICAL STUDY

SURENDRA B. PRASAD

Physics Department, School of Pure and Applied Sciences, University of the South Pacific, P.O. Box 1168, Suva, Fiji

(Received 17 August 1993; received for publication 26 July 1994)

Abstract—The theoretical performance of a biomass-fuelled boiler/steam power cogeneration system is investigated. The system performance is based on the known or assumed properties of the biomass fuel (its size, elemental composition, moisture content), energy content of the combustible constituents of the fuel, actual performance of a piston-operated-valve (POV) reciprocating engine and an alternator from earlier studies, and load profiles. Steam engine performance has been the subject of detailed studies at the Energy Research Center of the Australian National University (for example, Refs [1] and [2]), and these studies are referred to for steam engine performance for a given engine configuration. While the theoretical performance of a biomass-fired boiler is the major focus of this paper, experimental results from tests carried out on a sawdust-fired twin-chambered furnace/monotube boiler system are also addressed.

Biomass combustion   Steam power system   Steam engine performance   Cogeneration
Monotube boiler   Wood-fired boiler system   Boiler efficiency   Overall performance

INTRODUCTION

Biomass-fuelled steam power systems, providing electricity as well as process heat, have been utilized for many decades in most countries of the world. In the U.S.A., for example, such systems have found widespread applications in various industries dealing with wood or metal products, such as paper and pulp sawmill, veneer, plywood, metallurgical and other industries. These industries get up to 100% of their energy requirements from biomass fuels [3]. A great deal of research, development and demonstration has been carried out on biomass energy conversion systems [4–11].

In such systems utilizing the energy in the biomass fuel through the process of direct combustion to generate steam for driving a steam engine or turbine, the prime mover is the component that severely limits the system electrical output and efficiency, as a consequence of the second law of thermodynamics. Thus, steam engines and turbines up to a MW rating have efficiencies below 22%. Therefore, over three-quarters of the thermal energy supplied to a steam engine is rejected as low grade heat energy in a power generation facility. However, if this exhaust heat can be used for some process, then the energy and economic balances can be radically altered. For example, the exhaust heat from the engine or turbine can be used for drying crops, providing hot water, or even for drying the fuel fed to the boiler.

In this paper, an attempt is made to analyse a biomass-fuelled steam engine-based electricity and heat cogeneration system from both theoretical and experimental standpoints. It is important to do this in order to observe the effect of the various variables on system performance, for instance the amount of fuel required to generate a kWh of electricity under various conditions. Attention is focused on the two major components of such a system: the boiler and the prime mover. The boiler performance is studied on a theoretical basis, and this is combined with the actual performance data of a 3-cylinder reciprocating steam engine to arrive at the overall system performance.

Figure 1 shows a block diagram of a typical biomass-fired congeneration system. A brief description of the system operation may be useful at this stage. Biomass fuel is introduced, either manually or automatically, through a feed system into the furnace, where it is burned with air.

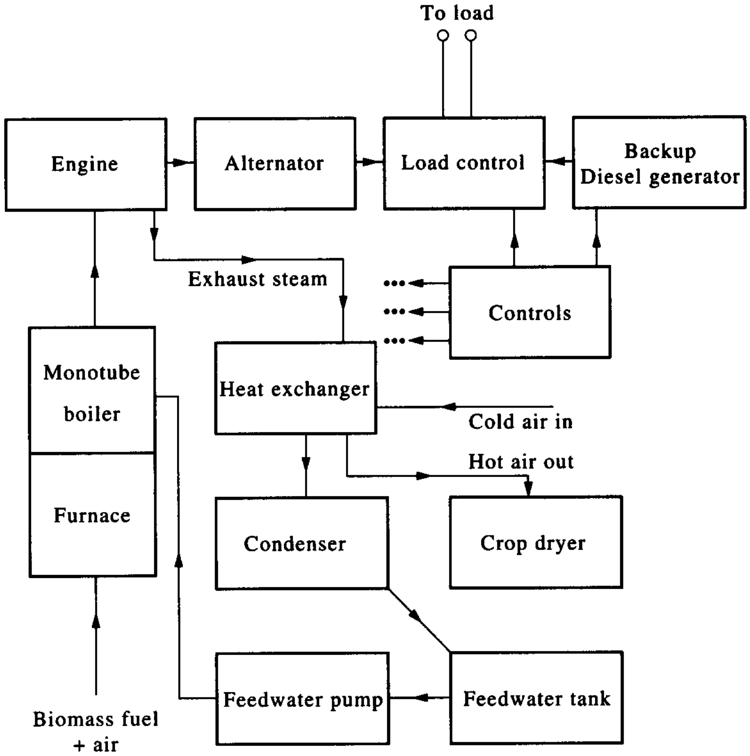

Fig. 1. Block diagram of a biomass-fired cogeneration system.

Combustion is controlled through either controlling the air flow rate, fuel flow rate or a combination of both. The products of combustion pass through the boiler where they give up the heat they carry to the water flowing through the tubes of the boiler, thereby generating steam.

The steam is piped to a steam engine where the heat in the steam is converted into rotary motion of a shaft. The mechanical energy of the shaft is converted to electrical energy by an alternator. The exhaust heat from the engine can be used in a heat exchanger to generate hot air for crop drying or for other process heat applications. The steam flowing out of the heat exchanger is condensed and pumped back by the feedwater pump into the boiler. A control and protection system is needed to control, monitor and protect the various processes and components.

THEORETICAL BIOMASS-FIRED BOILER PERFORMANCE

A biomass-fired boiler system is a complex system with several sub-systems for fuel drying, storage and handling, fuel combustion, feedwater treatment, air and water inlet control to the system, emission control, ash handling and, of course, steam generation. Basically, the system consists of a fuel shed where the fuel is stored; a chipper or hog to break the fuel into small, convenient pieces for proper combustion; a dryer to dry the fuel before being burned; a conveyor system which feeds the fuel into the primary combustion chamber (or gasifier) of the furnace where the fuel is burned; the secondary chamber where the gases released are burned; fans to control the air and flue gas movement and the boiler proper in which the energy of the flue gases is transmitted to the water and steam is generated.

Figure 2 shows a general block diagram of a small-scale biomass-fired boiler system.

Boiler losses can be significant, depending on the boiler design, the fuel used and the rates of air and fuel supplied, all of which determine combustion rate. The general reaction when fuel is burned in oxygen can be written as:

$$\text{fuel} + \text{oxygen (air)} \rightarrow \text{reaction products} + \text{energy}.$$

The reaction 'products' include carbon dioxide, carbon monoxide, nitrogen, water (steam), and

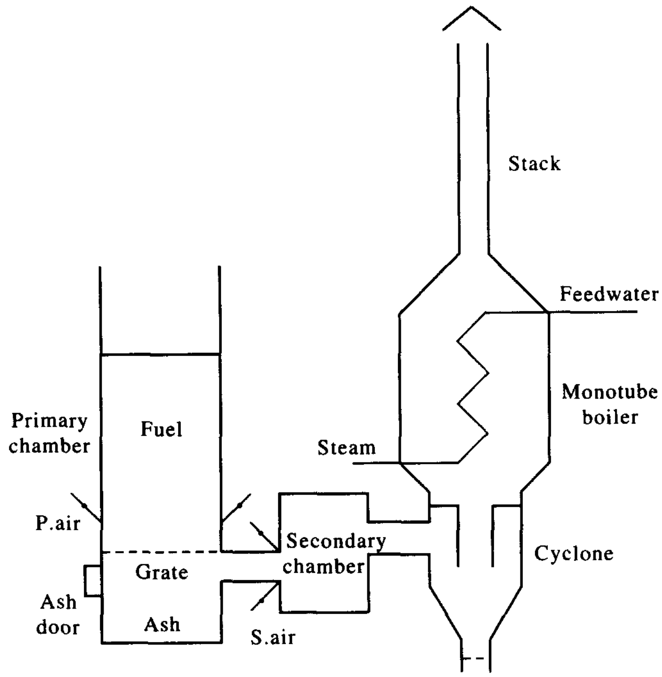

Fig. 2. Block diagram of a wood-fired boiler system.

may, depending on the ash content and the combustion temperatures, contain sulphur dioxide, particulates (char particles, etc.), nitrous oxide and other oxides of nitrogen.

The major losses of energy from the boiler include:

(1) heat carried away by the flue gases (dry products of combustion) including CO_2, CO, N_2, O_2, etc.;
(2) heat needed to evaporate water from the fuel and the air;
(3) heat taken away by the wet combustion product, namely water (steam);
(4) radiation and convection losses;
(5) loss due to incomplete combustion;
(6) energy loss to the ash.

Of these losses, the major loss is the energy loss of the flue gases exiting the boiler. This can be as high as 40% of the energy contained in the fuel, depending on the fuel and air moisture contents and the amount of excess air used. The second and fourth losses can be minimized more than the others. By using completely dry (oven-dry) fuel, the loss of heat due to the evaporation of water is minimized. For the loss of heat due to incomplete combustion, controlling the amount of combustion air can minimize the loss, although at the expense of losing more heat to the stack through the extra nitrogen and water vapour.

The chemical composition of biomass includes carbon, oxygen, hydrogen, sulphur and other chemicals in small quantities. The general breakdown of the composition is shown in Table 1. It should be noted that the chemical composition of various wood species varies considerably. Of particular importance and interest is the variation of the ash content in the various wood species, as it is the ash which contains sulphur and thus results in flue gases containing SO_2. The ash consists of oxides of metals, typically sodium, potassium, calcium and others.

BOILER ANALYSIS

In the following boiler analysis, sawdust is used as the furnace fuel. Sawdust has a variable energy content, depending on the species of wood from it originates and its moisture content. It also has a low ash content and burns very well when dry. Table 2 shows a list of the boiler unit input variables used for the boiler modelling.

The analysis is started by considering a unit mass (1 kg) of sawdust of various moisture contents and calculating the boiler losses and efficiency as a function of the moisture content. The major reactions inside the furnace between the fuel (sawdust) and oxygen (from the fuel and air), depending on the chemical composition of the fuel, include the following:

$$C + O_2 = CO_2 + \text{energy}$$

$$2H + 1/2O_2 = H_2O + \text{energy}$$

$$S + O_2 = SO_2 + \text{energy}$$

$$2CO + O_2 = 2CO_2 + \text{energy}.$$

Since combustion is an extremely complex process, a whole range of reactions is possible; however, the desired end reactions are those that lead to the complete oxidation of the combustible elements, i.e. carbon, hydrogen and sulphur. Fuel combustion depends on three main factors: Time, Temperature and Turbulence (these are commonly referred to as the three T's of Combustion). The minimum amount of air required for complete combustion of the fuel (known as the bf stoichiometric air) can be determined easily, given the elemental composition and moisture content of the fuel. In practice, however, this amount of air is not sufficient to ensure complete combustion, as all of the fuel cannot be in intimate contact with oxygen. In order to maximize the degree of combustion completeness, extra air, over that of the stoichiometric air (called, appropriately, bf excess air), is introduced into the furnace.

Thus, the total air required is given by the minimum air required multiplied by (1 + excess), where excess is the fraction of the minimum air used, above the minimum required.

If the fuel is not completely dry, then the chemical composition of carbon, oxygen, hydrogen and the other constituents of the fuel would be lower than that for the dry fuel. If a unit mass of fuel, as used in the boiler, contains x kg of water, then the mass of the dry fuel is $(1 - x)$ kg. The composition of the constituents of the wet fuel is, thus, reduced by a factor of $(1 - x)$.

The energy content of different biomass fuels varies considerably in the different categories of biomass, such as forest residues, crop residues, sawmill residues, waste products, etc. The heating value of different species of wood fuel, for example, varies considerably depending on the chemical composition, density, moisture content and other factors. The variations range from 9.9 MJ/kg for green wood of elemental composition [C, H, O, S, ash: 40, 5, 50, 0, 5% (50% m.c.] to 19.8 MJ/kg for bone-dry, high density wood. For sawdust, of elemental composition (C, H, O, S, ash: 44, 7, 45, 2, 2%), the heating value when completely dry is 23.9 MJ/kg. The heating value of biomass decreases, almost in direct proportion, with an increase in its moisture content. Thus, if a unit mass of biomass fuel has a moisture content of 50% (wet basis), then its heating value is roughly 50% of that when it is bone dry.

Table 1. Average chemical composition of biomass fuels

Chemical	Percentage range
C	40–50
O	40–50
H	4–10
Ash	0–4
N	0–1

Table 2. Boiler input variables

Input variable	Value
System capacity	30 kW
Average electrical load	15 kW
peak electrical load	25 kW
Fuel composition:	
C	0.44
H	0.07
O	0.45
S	0.02
Ash	0.02
Fuel moisture	30% (wb)
Excess air	50%
Stack exit temperature	200°C
Ambient temperature	25°C
Hours of operation	24 h/day
Heat of reaction for elements:	(MJ/kg)
C	32.8
H	133
S	9.7
CO	10.1

LOSSES OF ENERGY IN THE BOILER

Loss of heat to the flue gases

The flue gases are the dry products of the chemical reactions between the fuel and oxygen, and include CO_2, O_2 and N_2 as the major components. During the course of the reaction, these gases are liberated, forced to flow across the boiler tubes and eventually escape through the chimney, taking away heat from the boiler. The loss of heat to a particular flue gas per kg of dry fuel is given by

$$\text{loss} = \text{mass (flue gas)}\ X\ C_p\ \text{(flue gas)}\ X\ T$$

where mass (flue gas) is the mass of the flue gas; C_p (flue gas) is the average specific heat of the flue gas in the boiler and T is the temperature difference between the flue gas at the exit and the fuel before combustion.

On the basis of complete combustion of the fuel and calculations of the masses of the gases which constitute the exit products and the specific heats of the individual gases, the heat carried away by the flue gases can be determined. Depending on the fuel moisture, temperature of the flue gases as they leave the boiler and the amount of excess air, the loss of heat to the flue gases can be a substantial portion of the heating value of the fuel, the normal range being from 10 to 30%.

Loss of heat in evaporating the moisture

If the fuel (and air) is not completely dry, some energy is expended in evaporating the water from it. The amount of energy needed depends, of course, on the moisture content of the fuel and air and on the temperature of the wet product of combustion, i.e. steam. To evaporate 1 kg of water completely from 0 to 100°C requires an amount of energy equal to the sensible heat of water at 100°C plus the latent heat of water at 100°C. If the steam is superheated, an amount of heat given by the products of the mass of steam, the specific heat of superheated steam and the temperature difference between the steam temperature and 100°C is needed.

Loss of energy due to unburnt fuel

This loss obviously depends on the amount and humidity of air available for combustion and on the quality of the fuel. In the case of a deficiency of air for complete combustion, the unburned fuel, mainly carbon, escapes with the flue gases, carrying some heat in the form of a fraction of the heating value of the original fuel. Some heat is also carried by the hot unburned ash in the fuel, the ash dropping to the grate of the furnace. This loss is no more than of the order of 2%, depending on the ash content and combustion air supplied.

Radiation and convection losses

These losses are determined by the rate of fuel burning, the combustion temperature, the amount of air per kg of fuel, the material of the boiler and the insulation used, if any. These losses can vary between 2 and 5% under normal circumstances. In the subsequent analysis, this loss is taken as 5% of the energy input to the furnace, i.e. a fairly low degree of insulation is assumed.

THEORETICAL BIOMASS-FIRED BOILER PERFORMANCE

The performance of a theoretical biomass-fired boiler is analysed from the standpoints of the fuel quality, air input, electrical power output and energy content of the fuel. As a start, it is useful to calculate the energy losses in the boiler as a percentage of the energy input from unit mass of fuel of varying characteristics.

In the discussion that follows, a unit mass of fuel, of variable moisture content (m.c.) [0–70% (wet basis)] is burned in a boiler, and the heat balance is calculated. Figure 3 shows the boiler efficiency as a function of the fuel moisture content for three values of excess air, these being 0, 100 and 200%. The efficiency, it is observed, decreases with moisture content almost in a linear manner to a m.c. value of 50%, beyond which it decreases rapidly with increasing moisture content. For an exit stack temperature of 200°C and an excess air percentage of 100, the efficiency decreases from 79.2% (bone dry fuel) to 54.0% for fuel which has 70% moisture on a wet basis.

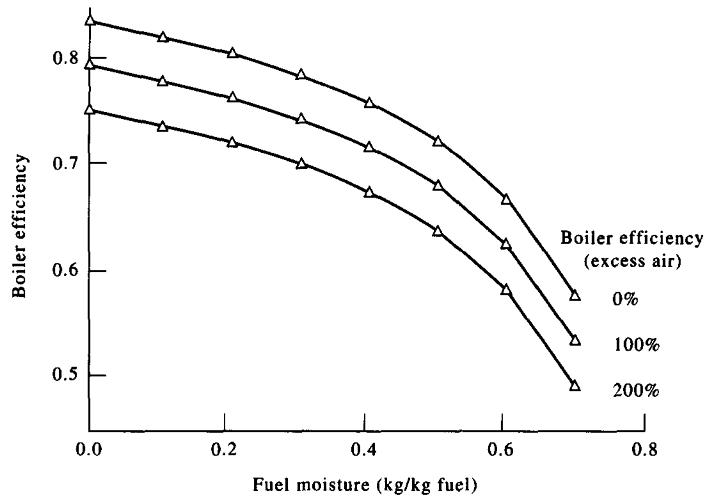

Fig. 3. Boiler efficiency as a function of fuel moisture content.

This increase in the loss of heat is partly due to the fact that a large mass of water needs a large amount of heat to evaporate it. Additionally, moisture in the fuel decreases the actual mass of the elemental components per unit mass of fuel with the result that less energy is available from the combustion of that unit mass of fuel, i.e. the higher (and lower) heating values of the fuel are reduced. The major losses of heat due to the removal of water from the fuel occur as a result of the following:

(1) heating the water in the fuel from the initial temperature to the boiling temperature of the water (sensible heat loss) and
(2) evaporating the water to steam (latent heat loss).

Both these losses are directly proportional to the mass of 'free' water in the fuel. The boiler efficiency also decreases with increasing excess air input to the furnace. For example, for bone-dry fuel, the boiler efficiency decreases from 83.4% for the minimum air required to 74.9% for a 200% excess air level, a drop of over 8%. For a fuel moisture of 60%, the efficiency decreases from 67.2 to 58.8% for the same excess air level change. The exit temperature in the stack is taken to be 200°C for these cases.

Since the largest loss in the furnace/boiler unit is that due to the stack gases leaving the chimney, it is instructive to observe the dependence of this loss on the temperature at which the gases leave the stack. The stack exit temperature, at the point where the heat carried by the gases does not contribute to the energy gain of the steam, varies considerably due to factors such as the design and width of the stack, the boiler insulation, the design of the boiler tubes and the pressure differential between the bottom and top of the stack. Variations in stack temperatures ranging from 60 to 160°C have been actually observed for a particular system [1].

By varying the stack exit temperatures from 100 to 300°C, the effect of this variable on boiler efficiency for a constant excess air level of 30% has been computed for three values of fuel moisture [0, 30 and 60% (wet basis)]. These calculations show that the boiler efficiency decreases with increasing stack exit temperature in a fairly linear manner. This is to be expected since, for each stack temperature, the other losses are constant. For bone-dry fuel with an excess air fraction of 0.3, the boiler efficiency decreases from 85.8% (stack exit temperature of 100°C) to 78.4% (exit temperature of 300°C), a decrease of 7.4%. For fuel of 60% moisture, the corresponding figures are 69.6 and 62.3%. The small effect due to the change in the specific heat capacity of the stack gases with temperature has been ignored. It should be noted that an increase in the stack exit temperature must be accompanied by an increase in boiler heat loss due to radiation and convection, as the furnace and boiler walls are at higher temperatures.

EXPERIMENTAL BIOMASS-FIRED BOILER PERFORMANCE

A sawdust-fuelled, 2-chambered furnace/boiler system was tested between May and July 1988 at the Australian National University laboratory of the Department of Engineering Physic's Energy Research Center. The rated thermal output of the boiler is 170 kW at the steam outlet pressure and temperature of 6 MPa and 400°C, respectively.

Each combustion chamber has its own (adjustable) air supply, primary air being admitted through holes in a plenum (60 cm above the furnace bottom) around the primary chamber and secondary air being delivered through angled openings to the secondary chamber from a plenum.

The moisture content of the sawdust fired during the tests varied from 24 to 43% (wet basis), with the average of all the runs being 35%. Thus, there was considerable variation in the fuel moisture, as a result of which, the boiler steam quality was also quite variable due to the rapidly changing fuel combustion rate.

The measured boiler performance for the three best runs is shown in Table 3. The table includes values of the average moisture content, fuel flowrate, steam flowrate, temperature and pressure, average energy input to the furnace (as stored chemical energy of sawdust), boiler output and efficiency. The pressure difference between the feedwater inlet and steam output ranged between 200 and 300 kPa.

DISCUSSION OF RESULTS

Temperatures inside the stack at the bottom and top were monitored throughout the testing period. It was noted that the two temperatures were not very different, the maximum difference being 10°C. The highest temperature of 160°C indicates a reasonably good heat transfer from the gas to the boiler. Steam output ranged from 132 to 166 kW, with corresponding furnace/boiler efficiency of 56–71%.

The average moisture content for the sawdust sample was 0.35 kg/kg fuel (35% on a wet basis). The average fuel firing rate was 0.02 kg/s, the ambient temperature was 14°C, and the furnace/boiler unit was steadily fired for over 3 h for each run.

The volumetric composition of the flue gas was CO_2: 12.8%; O_2: 8.2%; CO: 0.0%. A carbon balance yields a stoichiometric oxygen requirement of 0.85 kg/kg fuel. From this and the oxygen content of the flue gas, the total air used is calculated to be 5.96 kg/kg fuel. This enables the excess air used to be determined—this is 66%. As a check of this value, the measured air rates also enable the determination of the amount of excess air. From the exit temperatures of the flue gases, the combustion temperature inside the furnace and the furnace wall temperatures, the heat losses from the furnace/boiler unit are determined and are as follows:

Heat input to furnace (from fuel) = 0.02 kg/s*11,700 kJ/kg = 234 kW
Heat loss to conduction and radiation from furnace walls = 11.7 kW
Heat loss due to flue gases = 40.9 kW
Heat loss to evaporate moisture from fuel = 18.4 kW
Steam pressure = 4.2 MPa

Table 3. Measured performance of furnace/boiler unit
Measured boiler performance

Date	Moisture (% wet basis)	Fuel rate (kg/s)	Steam flow (kg/s)	Steam pressure (MPa)	Steam temp. (°C)
23 June 1988	33	0.024	0.0695	3.5	235
25 June 1988	35	0.020	0.0495	4.0	484
30 June 1988	35	0.0152	0.0425	3.4	370

Summary of boiler performance

Input (kW)	Output (kW)	Efficiency (%)
289	181	61
234	166	71
178	132	78

Table 4. Comparison of engine tests at White Cliffs and ERC

Variable	Tests at White Cliffs [1]	Tests at ERC [2]	Unit
No. of runs	45	205	
Inlet steam pressure	3.5–4.9	1.8–5.84	MPa
Inlet steam temp.	243–416	260–430	°C
Heat input	119–157	110–195	kW
Steam flowrate	0.03–0.048	0.043–0.065	kg/s
Exhaust temperature	75–87	—	°C
Feedwater temperature	35–63	32–56	°C
Condenser pressure	35–60	5–55	kPa
Engine output	9.5–17.7	14.7–33	kW
Engine efficiency	8–15	11.7–17.5	%

Steam temperature = 465°C (212° of superheat)
Feedwater flowrate = 0.0495 kg/s
Measured boiler output = 164 kW
Measured boiler efficiency = 70%
Theoretical boiler output = 163 kW
Theoretical boiler efficiency = 69.6%.

ACTUAL STEAM ENGINE PERFORMANCE

The theoretical performance of a POV reciprocating, condensing steam engine has been studied extensively by Prasad [1] and Bannister [2], both of whom studied at the Energy Research Center, Research School of Physical Sciences and Engineering at the Australian National University. Prasad developed a theoretical model for the White Cliffs steam engine and validated the theoretical results with actual data obtained from the White Cliffs engine. The data obtained were those from the engine in normal operation and, therefore, do not show the range and variability as those obtained by Bannister at the ERC in Canberra. The White Cliffs engine test results do not represent a true experimental set-up, as there were constraints as to the degree of variation in engine inlet parameters allowed in a situation in which the system was supplying continuous power to the load. Table 4 compares the experimental performance of the White Cliffs and the Energy Research Center engines.

Because of the much better control over all the different variables involved in the performance of a steam engine, Bannister obtained more accurate and reliable engine performance results over a wider range of inlet and exit conditions than was possible at the White Cliffs site. Because of this, the results from Bannister's study have been used in this study to determine engine performance, given the value of one of the input variables.

Table 5. Sample steam engine performance data

Heat input (kW)	Mass flow (kg/s)	Pressure (MPa)	Temperature (°C)	Output (kW)	Efficiency (%)
123.9	0.04306	3.285	262.8	15.95	12.87
130.3	0.04532	3.525	265.5	17.06	13.09
127.6	0.04351	3.595	286.0	17.63	13.81
177.0	0.05975	4.793	311.7	27.22	15.38
176.4	0.05781	5.122	345.7	28.95	16.41
174.6	0.05516	5.361	391.1	29.37	16.82
173.9	0.05371	5.292	419.7	29.42	16.92
190.6	0.06482	5.209	309.7	29.50	15.47
175.7	0.05644	5.306	369.9	29.65	16.88
191.5	0.06430	4.932	317.8	29.84	15.59
190.3	0.06259	5.490	345.6	30.94	16.26
189.4	0.06090	5.710	372.5	31.66	16.71
194.2	0.06369	5.152	345.6	31.94	16.44
188.9	0.05962	5.807	396.1	31.94	16.91
188.4	0.05815	5.660	423.1	32.47	17.24
194.6	0.06241	5.395	372.8	33.08	17.00

Table 5 shows a sample of the steam engine performance data, giving the inlet steam pressure and temperature, steam flowrate, heat input, engine output and efficiency.

METHOD OF UTILIZING STEAM ENGINE PERFORMANCE DATA

The major variables that affect steam engine performance include the inlet steam pressure and temperature, steam flowrate, thermal input and condenser pressure. The engine performance look-up table consists of values of inlet steam temperature and pressure, mass flow, heat input, engine output and efficiency. For the particular engine being modelled, the expansion ratio (15.8) and condenser pressure (25–35 kPa) are fixed. Thus, if any of the inlet variables are known, the power output and efficiency of the engine can be determined from the table.

Because of the complex interrelationships between engine output and efficiency and the engine inlet variables, a particular value of any of the engine inlet variables can yield more than one value of engine output and efficiency. This is illustrated in Fig. 4(a) and (b) which are plots of engine output and efficiency, respectively, as functions of the inlet variables.

The program for determining the engine performance uses an algorithm that makes several passes of the data table, each time with new information on engine inlet variables, that finally yields the 'right' engine efficiency or other desired information. Thus, if only the power required from the engine is known, the program simply finds the first value of the power output from the table that is within a certain given percentage of the desired value and computes the values of the other parameters. Thus, crude values of steam inlet pressure and temperature, steam flowrate, heat input and efficiency can be determined after the first pass of the data table. Then, once the heat input to the engine is known, the power output and heat input can both be used to get the engine performance data, and so on.

The actual working of the program to determine engine efficiency is now discussed in detail. First, given the load demand and the average alternator and the transmission and distribution efficiencies, the engine output is determined. This is the net engine output which excludes the power required to drive the auxiliary equipment, including the required station electricity use. For this, a certain fraction, between 5 and 15%, depending on the number and ratings of the auxiliary devices (such as motors and lights), is used for the power used by these devices. This fraction is added to the power required from the engine. This value is then used to get a first approximation of the other engine data.

Thus, after the first pass of the table, the heat input to the engine is obtained. The method used to actually get the values needed from the look-up table uses two basic approaches. In the first case, the exact match or a match within 5% of the given value is obtained. The corresponding values of the other parameters are then simply read off the table. If this is not possible, then linear

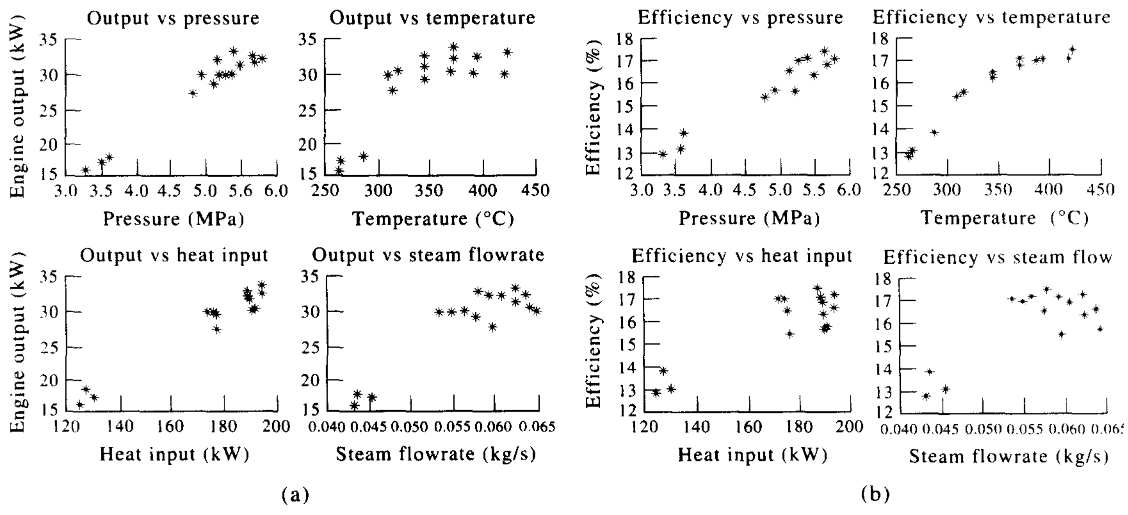

Fig. 4. Variation of engine output and efficiency as functions of inlet variables.

extrapolation is used to compute the values required. As more values of the engine inlet variables are known, the extrapolation gets more accurate.

After the first pass, the heat input to the engine is found. This is then used to determine the fuel flowrate to the boiler. This is obtained on the basis of the calculated higher heating value (HHV) of the boiler fuel, the HHV itself being calculated from the known or assumed elemental composition of the fuel and an initial, assumed value of the boiler efficiency (chosen to be 50%). The heat input to the furnace and the bf required boiler output are repeatedly used to obtain the actual fuel feed rate that will produce the desired boiler output. After each cycle, a new value of the boiler efficiency is obtained, which leads to a new value of the energy input to the furnace and this, in turn, yields a new value of the fuel flowrate. This process finally leads to an estimate of the boiler output, i.e. the thermal power carried to the steam engine.

The steam flowing from the boiler to the engine suffers some loss, this being dependent on the length of the steam line and the degree of insulation of the steam pipe. This loss is calculated from a knowledge of the length of the steam line and the heat loss per unit steam line length, which is taken from the tests carried out at the ERC on steam pipe losses by Bannister.

The heat input required by the engine and the engine power output are now fed to the program to determine the values of steam flowrate and engine efficiency. This steam flowrate is used with the engine inlet pressure and temperature values obtained from the earlier pass to get the engine output. If the output is not in agreement with that required, a new iteration is initiated, a new value of engine heat input is found, and the cycle is repeated until the power required and that obtained from the table are in close agreement. In the end, the program outputs include the engine efficiency for the given or calculated engine inlet conditions as well as those conditions which are not known initially.

PERFORMANCE OF OTHER COMPONENTS

The other components in the power supply system include the alternator, feedwater pump, vacuum pump, cooling water pump, heat exchanger, crop dryer, and condenser. The performance of these has not been studied in detail due mainly to the fact that, by and large, they do not make any significant difference to the overall system performance. In any case, the study deals primarily with boiler performance, and detailed modelling of auxiliary components is outside the scope of this study. Some general words on these components is believed to be necessary, however.

The performance of the pumps used in the power supply system have been taken into account by allowing an adjustable fraction of the engine output to be used by auxiliary equipment. Thus, a value between 5 and 15% of the engine output is taken to be that used by the motors running the various pumps in the system. The alternator performance has been studied extensively by Bannister [2], and his measured results indicate that the alternator has an efficiency of over 91% for all his test runs (76 runs for an expansion ratio of 15.8). The *measured* efficiency of the alternator that he carried out tests on (64 kW moving field Newage C30B alternator) ranges from 91.14 to 93.37%. For the purpose of this study an alternator efficiency of 92.65%, being the average figure for the alternator efficiency taking all tests into account, is taken. For the transmission and distribution of the single-phase electricity (with an average transmission distance of only a few kilometers), and efficiency of 98% is assumed.

The auxiliary equipment is assumed to operate at peak efficiency. From actual data taken from the White Cliffs solar thermal power station in northwestern New South Wales, the motors driving the feedwater, vacuum and cooling water pumps all have efficiencies of around 90% and take in around 5 kW of electrical power. As the nominal engine power output is 30 kW and the peak electrical demand is taken to be 25 kW, the engine has little difficulty in providing enough power to the auxiliary components.

OVERALL SYSTEM PERFORMANCE

The system generates electricity (single-phase a.c.), as well as process heat for crop and/or fuel drying. The generation of electricity is the primary objective, and the minimization of unit electricity is a prime target. From the preceding sections, it is quite clear that the steam engine puts

Table 6. Range of system performance data

Range of variables	
Fuel moisture	: 0–60% (wet basis)
Excess air	: 0–200%
Stack temperature	: 100–300°C
Expansion ratio	: 15.8 (fixed)
Condenser pressure	: 25–35 kPa

Component	Lowest efficiency	Highest efficiency	Comments
Boiler	49	86	Theoretical
	60	78	Measured
Steam engine	11	17.5	Measured
Alternator	90	93	Measured
Heat exchanger	60		Assumed
System	8.4	11.9	Theoretical

a fundamental limit on the overall system efficiency. The best value of engine efficiency, obtained from the ANU 3-cylinder POV engine has been measured at 17.5% [2], while the best figure for a monotube boiler performance is 79% [1]. Thus, with these two major components, the overall system efficiency is necessarily below 14.6%. The performance of the various components of the system, discussed in earlier sections, is now combined to give a picture of the overall system performance for electricity generation alone and for the cogeneration mode. Table 6 gives the best and worst performance data for the system components and the overall system.

In the cogeneration mode, the amount of process heat required can be adjusted by adjusting the condenser pressure. That is, if an increase in heat for drying is required, this can be accomplished by a corresponding increase in the condenser pressure which decreases the engine mechanical output and, for a given heat exchanger efficiency, increases the thermal energy input to the exchanger. For this study, the heat exchanger efficiency has been taken to be a conservative 60%.

The program also determines the annual and energy costs of the system. This is done on the basis of known or estimated values of the costs of the various components (boiler, engine, alternator, condenser, heat exchanger, feedwater pump, auxiliary equipment and controls), annual maintenance and labour costs, costs for the buildings, engineering works, installation and transmission. Component lifetimes are also sensibly assumed, with a system lifetime of 20 yr taken. The electricity generated over the lifetime is computed, taking an outage period of 2 wk. Annual cost, installed cost (total lifetime cost divided by the installed capacity) and energy cost are also determined.

The variation of the electricity/fuel mass ratio (i.e. the amount of electricity generated from unit mass of fuel) and overall system efficiency as functions of fuel moisture for a constant system operation of 24 h/day is shown in Fig. 5. The boiler variables are: average load 15 kW, excess air 50% and stack temperature 200°C. The steam engine efficiency is determined to be 15%, the electricity to fuel ratio varies from 0.64 kWh/kg for bone-dry fuel to 0.20 kWh/kg for fuel of 60%

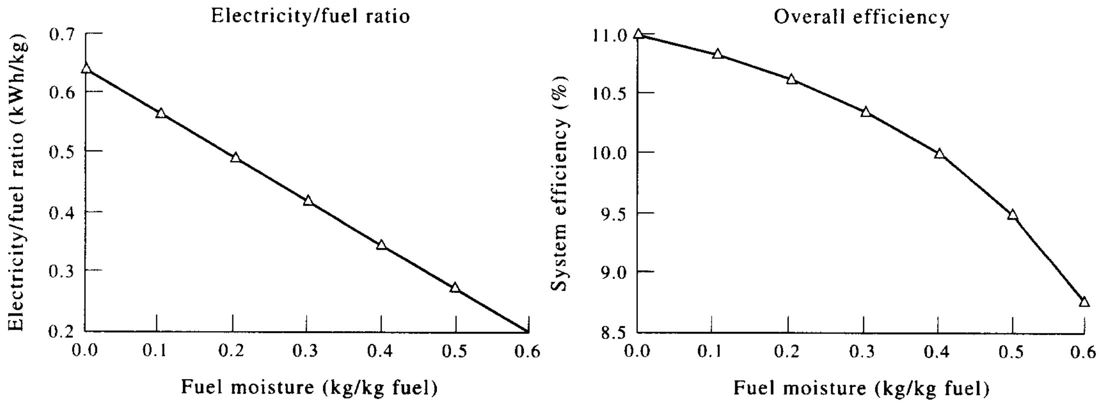

Fig. 5. System performance as a function of fuel moisture.

moisture; the overall system efficiency decreases from 11 to 8.8% for the same fuel moisture variation. Electricity cost increases from 10 c/kWh (0% moisture) to 13.7 c/kWh (60% moisture).

CONCLUSIONS

The aspects of theoretical and experimental performance of a biomass-fuelled, steam-powered electricity/heat cogeneration system have been studied and discussed. The main focus of the study has been the theoretical performance of a biomass-fired furnace/monotube boiler unit and the performance of a specified steam engine coupled to the boiler, based on the actual performance of a 3-cylinder POV reciprocating steam engine. The system, as modelled, consists of a furnace/boiler unit, a high performance steam engine, an alternator, heat exchanger, condenser and other auxiliary units.

The boiler performance was based on a given fuel and its characteristics (type, moisture content, elemental composition and heats of reaction of the constituent elements), excess air to the furnace and assumed stack exit temperatures. The principal loss of heat in the boiler is that due to the heat carried away by the products of combustion (stack gases). This ranges between 5 and 30% of the energy contained in the fuel. The second major loss is the energy required to evaporate the fuel moisture; this can account for up to 24% of the energy input to the boiler, depending on the fuel moisture and the amount of excess air. Other losses include the radiation and convection loss, the energy loss due to incomplete combustion and the energy carried away by the hot ashes falling through the grate. Boiler efficiency is strongly affected by fuel moisture, falling from 79.2% for bone-dry fuel to 54.0% for 70% wet fuel (wb) and with an excess air fraction of 100%, for an exit stack temperature of 200°C.

The steam engine performance data has been taken from studies carried out at the Energy Research Center, Research School of Physical Sciences and Engineering and the White Cliffs solar thermal power station [1, 2]. The thermal energy steam from the theoretical boiler is converted to mechanical energy by the steam engine which, in turn, drives an alternator which generates single phase electricity. The exhaust steam from the engine is used by a heat exchanger to provide heat for crop or fuel drying.

For the given engine (with its fixed expansion ratio of 15.8 and condenser pressure ranging from 25 to 35 kPa), the power output and efficiency range from 15.95 to 33.08 kW and 12.87 to 17.24%, respectively. The alternator efficiency has been taken to be 92%, based on actual tests on a particular type of alternator used at the ERC [2]. An efficiency of 60% has been taken for the heat exchanger.

The overall system output depends on the fuel flow rate, boiler input conditions and fuel properties, and for the 30 kW capacity system being modelled, ranged up to 27 kWe. Overall system efficiencies lie between 8 and 11%. The corresponding figures for the electricity to fuel consumption ratio is between 0.20 and 0.65 kWh/kg fuel for fuel moisture varying between 60 and 0% (wet basis) and an excess air level of 50%.

The study has shown the effect of the various variables on boiler performance and has shown the dependence of the system output and efficiency on steam engine inlet conditions.

This study can be extended further to deal with the variables not considered in detail, such as the detailed temperature distribution on the outer walls of the furnace/boiler unit, giving rise to accurate radiation and convection losses, the loss due to unburned fuel by considering the actual mechanism of combustion in specific detail, the precise calculations of stack exit temperature and greater attention paid to the heat exchanger, among other possibilities. All of these were outside the scope of this work, the major objective of which was to combine a biomass-fuelled boiler unit with a steam engine and to model the overall steam power system with respect to the major input variables.

Such studies given a useful insight into the performance of electricity/process heat cogeneration systems utilizing biomass fuels of variable properties. The results of this particular study show that, for systems using biomass fuels between 0 and 60% (wet basis) and excess air rates between 0 and 200%, boiler efficiencies range from 84 to 49%; steam engine efficiencies from 18 to 13% and overall plant efficiencies from 11 to 8.4%. The electricity cost varies between 10 and 14 c/ kWh and the electricity/fuel ratios between 0.7 and 0.2 kWh/kg.

REFERENCES

1. S. B. Prasad, A biomass-fuelled steam power generation system: modelling, performance and control aspects. Unpublished Ph.D. thesis, Energy Research Center, Australian National University, Canberra, Australia (1988)
2. P. B. Bannister, An experimental and analytical assessment of a steam Rankine solar thermal system. Unpublished Ph.D. thesis, Energy Research Center, Australian National University, Canberra, Australia (submitted November 1991).
3. D. A. Tillman, A. J. Rossi and W. D. Kitto, *Wood Combustion: Principles, Processes and Economics*. Academic Press, New York (1981).
4. Feasibility study on electric power generation from wood and coconut wastes. Government of Western Samoa (1982).
5. M. Z. Lowenstein (Ed.), *Energy Applications of Biomass*. Elsevier, Amsterdam (1985).
6. A. Strub, P. Chartier and G. Schleser (Eds), *Energy from Biomass*. 2nd European Community Conference. Applied Science Publishers (1983).
7. D. O. Hall, G. W. Barnard and P. A. Moss, *Biomass for Energy in the Developing Countries*. Pergamon Press, Oxford (1982).
8. K. V. Sarkanen and D. A. Tillman, *Progress in Biomass Conversion*, Vols 1 and 2. Academic Press, New York (1979).
9. P. N. Cheremisinoff and A. C. Morresi, *Energy from Solid Wastes*. Marcel Dekker, New York (1976).
10. S. S. Sofer and O. R. Zaborsky, *Biomass Conversion Processes for Energy and Fuels*. Plenum Press, New York (1981).
11. Cheremisinoff *et al.* (1980).